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Radiation Parameters of the VLF Transmitting Station NPM, Lualualei, Hawaii

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13. ABSTRACT

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The radiation parameters were determined at five test frequencies; 14.7, 16.6, 19.8, 23.4, and 28.5 kHz, with the transmitting antenna operating in a dual or parallel east and west array configuration and in a single east array. The parameters were also determined for the antenna system operating in a single west array configuration for four frequencies; 16.6, 19.8, 23.4, and 28.5 kHz.

A test to determine the possible onset of corona losses was performed with the dual array operating at 14.7 kHz, 23.4 kHz, and 28.5 kHz test frequencies.

The values for the radiation parameters as well as the results of the corona tests are reported and discussed herein, along with a detailed description of the experimental techniques and data reduction process.

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CONTENTS

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PROBLEM STATUS

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NAVAL ELECTRONICS SYSTEMS COMMAND

RADIATION PARAMETERS OF THE VLF TRANSMITTING STATION NPM, LUALUALEI, HAWAII

1.0 INTRODUCTION

A very-low-frequency (VLF) transmitting antenna has been constructed for the U. S. Navy at the Naval Transmitting Facility (call letters NPM), Lualualei, Hawaii. As a part of the Proof of Performance evaluation of the new antenna, personnel from the Naval Research Laboratory (NRL) determined the antenna system radiation parameters including radiated power, radiation resistance, and effective height, in November and December 1971. In addition the antenna system was tested for possible corona conditions. The NPM antenna basically consists of two, single, top-loaded vertical elements fed in parallel from a common junction point by two feedlines*, which differ appreciably in physical length. The difference in physical lengths of the two feedlines are required because the two towers are not symetrically located about the transmitter building and helix house. The longer feedline which feeds the far tower (east antenna array) is connected to the tower at the fourth guy level and also is electrically jumpered horizontally to two adjacent tophat radials. The short feedline is connected to the near tower (west antenna array) at a single point corresponding to the second guy level. The normal operating antenna configuration is with both the east and west arrays driven in parallel, but for emergency operation a single tower can be driven (either east or west array) with the unused tower grounded. The radiation parameters were measured at five operating frequencies (14.7, 16.6, 19.8, 23.4, and 28.5 kHz) with the antenna in its normal dual mode and also for the east array only. For the single west array configuration no test transmissions were made at the 14.7 kHz test frequency because the antenna matching network could not provide enough inductance to tune the antenna at this frequency. A test was performed on the dual array to determine the possible onset of corona losses while operating at the 14.7 kHz, 23.4 kHz, and 28.5 kHz test frequencies.

*These conductors might also be referred to as downleads, however because of the manner in which they are connected to the insulated vertical towers, the term feedlines seems to be more appropriate.

2.0 MEASUREMENT CONCEPTS AND TECHNIQUES

2.1 General

VLF antennas are, in general, electrically very short; that is, their physical dimensions compared to a wavelength are very small. The VLF transmitting antenna for NPM, Lualualei, is such an antenna, employing, in effect, two single vertical elements each with umbrella-type top loading, and fed in parallel from a common junction point by two feedlines. Only the vertical electric component of energy radiated from such a VLF antenna system contributes appreciably to the energy received in the far field. The top loading acts to increase the effective current distribution in the vertical conductor thereby increasing the radiated field.

The effective height of a transmitting antenna is a measure of its effectiveness as a radiator of electromagnetic energy. The radiation resistance of a transmitting antenna system is a fictitious quantity but it can be expressed as the resistance that, when inserted in series with the antenna will consume the same amount of power as is actually radiated. The radiation resistance, R_r, is used in determining the power, P_r, radiated by the transmitting station from the relation

$$P_r = I_a^2 R_r \qquad (2\text{-}1)$$

where, I_a is the transmitting antenna current.

For an antenna system such as that at NPM, neither the effective height nor the radiation resistance can be measured directly, or theoretically calculated from a practical model to a sufficient degree of accuracy. Both of these parameters can be calculated if the radiated power and corresponding antenna current of the transmitting system are known. The radiated power can be determined from measurements of the field strength existing at a known distance from the transmitting antenna. For the greatest accuracy, these field strength measurements should be made in the region where the field strength, E, is proportional to the inverse of the distance, d, from the transmitting antenna. Since the field strength measurements, even in this region are affected by local conditions such as abrupt changes in ground conductivity and more so by transmission lines, fences, etc., a large number of measurements must be made at many distances and bearings from the transmitting antenna to insure a high degree of overall accuracy

The radiation resistance, R_r in ohms, can be determined from the relation

$$R_r = \frac{d^2 E^2}{90\ I_a^2} \tag{2-2}$$

where, d is the distance from the transmitting antenna in kilometers, E is the field strength in millivolts per meter, and I_a is the antenna current in amperes. Using the same units and the frequency, f in kilohertz, the effective height, h_e in meters, is determined from

$$h_e = \frac{796\ Ed}{I_a f} \tag{2-3}$$

In a theoretical treatment of the radiation characteristics of an electrically short monopole antenna, the antenna current is normally considered to be the current at the base of the monopole. The radiation resistance under this idealized situation is the classical value for the antenna alone. For the practical situations involved with the subject system, the antenna current as measured and stated here is not necessarily the current at the base of the antenna and may include some loss currents. The radiation resistance obtained using these measured antenna currents is therefore an effective value influenced by these losses.

More details of the near-fields from a VLF transmitting antenna are given by Garner and Raudenbush (1).

2.2 Field Strength Measurements

The radiation resistance and effective height of the NPM transmitting system were determined from a large number of field strength measurements at known distances from the NPM antenna in the region where the field strength is proportional to the inverse of the distance. The field strengths were measured using DECO Field Intensity Meters, Model C400-A, manufactured by DECO Electronics. These equipments employ a loop antenna and are calibrated to measure field strength in dB relative to one microvolt per meter. It should be noted that these field strength measuring equipments with the shielded loop respond only to the magnetic field component of the electromagnetic energy radiated. However, if it is assumed that a free space impedence relationship exists between the electric and magnetic field components, the meter can be calibrated in terms of equivalent electric field intensity. Therefore the parameter

E in (2-2) and (2-3) used in calculating R_r and h_e is the value measured using these measuring equipments.

Special, two-minute, key-down transmissions were provided by NPM for the field strength measurements. In addition some field strength measurements were taken prior to these special transmissions while the transmitter was being tested by Continental Electronic Manufacturing Company (CEMC). These CEMC tests provided additional time to check old measurement sites for accessibility, possible field strength gradient and poor loop nulls and when necessary to relocate to a new site. Measurements were made at five operating frequencies, 14.7, 16.6, 19.8, 23.4, and 28.5 kHz, with the NPM antenna in the dual and east array configurations. For reasons stated previously in the report, the single west array configuration was not tested at the 14.7 kHz test frequency. The two-minute transmissions were started as soon as the transmitter was properly tuned (indicated by several short breaks in the transmission) to a test frequency. A two-minute transmission at the next test frequency was then made after the transmitter was retuned. This cycle was repeated until the measurements had been completed for all the site locations and at each test frequency for a particular antenna configuration. The dual array measurements were made on 2 December with some preliminary data also obtained on 23 and 24 November 1971 during the CEMC test runs. The east array measurements were made on 3 December also supplemented by some data taken on 26 November during the CEMC test runs. The west array measurements were made on 3, 4, and 6 December 1971.

Precautions were taken to ensure that the measurement sites were free from local anomalies in field strength, as might be caused by the effect of overhead power lines, fences, buried cables, or abrupt discontinuities in the conductivity of the terrain. The ratio of the maximum to the null signal level was noted (obtained by nulling the loop on the signal and then rotating the loop exactly 90 degrees) and sites having less than a 40 dB ratio were considered unsatisfactory. The existence of any appreciable gradient in field strength at each site was also determined by moving the loop to at least three locations separated a minimum distance of 50 feet, and measuring the field strength at each location. More than 0.2 of a dB change in field strength was considered unsatisfactory and the site was relocated. After the field strength readings had been taken at all the sites, a plot of field strength as a function of distance was made. Any site for which the field strength deviated more than 2 dB from the linear average was considered to be unsatisfactory and a decision was then made to relocate or eliminate that site.

There were two field strength measuring teams operating simultaneously in the field while another NRL representative recorded antenna

currents at the transmitter. Normally each team would make measurements at all test transmission frequencies at a particular site, and then move to the next site. Each team had a set of Geological Survey quadrangle maps pertaining to their areas, and the location of each measurement site was carefully indicated on the appropriate maps by the measurement teams.

The metering circuit of the C400-A Field Intensity Meter is such that field changes of 0.1 dB relative to one microvolt per meter are detectable, with estimates to the nearest 0.05 dB being possible. Each of these meters was accurately calibrated in a standard field using the two-loop method of calibration prior to and following the field measurements. No meter showed a change greater than 0.1 dB relative to one microvolt per meter over the period of the field measurements. A precise milliameter with an accuracy of 0.5 percent was used as the primary reference for the two-loop method of calibration, and also for standardizing each C400-A meter throughout the period in which field measurements were made. It is believed that the calibration techniques used resulted in measurement accuracies within plus or minus 0.1 dB relative to one microvolt per meter. To improve the overall measurement accuracy several measurements were made at some sites by different measurement teams.

2.3 Distance Measurements

It can be seen from equations (2-2) and (2-3), that the distance from the transmitting antenna to the field measurement sites should be measured to an accuracy as good or better than that of the field strength measurements in order to determine the radiation resistance and effective height to a high degree of accuracy, since the errors of E and d are additive. The island of Oahu is accurately mapped by the U. S. Geological Survey on quadrangle maps. Knowing the latitude and longitude of the measurement sites and the NPM transmitter location as scaled from the quadrangle maps the distances could be calculated using a computer program. The accuracy of these distances is believed to be commensurate with that of the field strength measurements.

2.4 Antenna Current Measurements

Although at the time of the NRL field strength measurements, the NPM antenna current meter had been calibrated, it should be noted that a frequency dependence does exist in the technique used to measure the antenna current. During the NPM transmitting system heat runs, conducted

by CEMC, the frequency dependence was discovered and investigations were carried out to determine not only the source of the problem, but to ascertain a valid method of obtaining the true antenna current. A detailed description of the final technique adopted by CEMC will not be discussed here, but basically it required a console mounted panel meter with a linear 0 to 100 scale, and then using a Pearson Electronics Standard Current transformer (0.01 volt/ampere) and a digital voltmeter as the reference current reading device, the antenna current was varied in steps for a particular test frequency. The panel meter readings and the antenna currents were recorded for each step over the selected range. This procedure was repeated until all the test frequencies had been covered. Finally, using the recorded data, a family of curves was plotted of antenna current versus panel meter numbers for each test frequency.

For the field strength measurements, an antenna current of about 85 percent of the CEMC suggested operating level for each antenna configuration was maintained as constant as possible. If any significant change in the panel meter indication did occur during the measurements, the meter reading was recorded and the corresponding antenna current was later extrapolated from the curves. It should be noted here that reading the panel meter accurately is quite important, especially in the lower portion of the scale. The deflection of the panel current meter varies as the square of the current, causing the lower portion of the meter scale to be extremely compressed. This means that the scale graduations for the smaller values of current, say below 400 amperes, could be as much as 20 to 30 amperes per scale division. Thus an error in reading of $\pm$ 5 amperes or more could occur with little difficulty, and in turn the values of the radiation parameters would reflect this error. This subject will be discussed further in the result portion of the report.

2.5 Corona Measurements

A test to determine the possible onset of corona losses for the antenna system when operated in the dual array configuration was performed on 7 December 1971 at the 14.7 kHz, 23.4 kHz, and 28.5 kHz test frequencies. The technique used was to first, tune the transmitting system to some nominal antenna current and then to continue transmissions in a key-down condition for two minutes to allow for proper orientation of the receiving loop. Next, the antenna current was reduced to a predetermined lowest usable value and a field strength measurement was taken in the key-down condition. The antenna current was then increased in given steps with a two-minute duration key-down transmission being

made at each increment to enable field strength readings to be taken. This procedure was continued until a highest predetermined value of antenna current was reached, with field strength readings taken at each two-minute key-down period.

For this test two fixed sites were chosen that appeared to give the most consistent results during the previous field strength measurements. Two teams operated simultaneously in the field while another NRL representative recorded antenna currents at the transmitter.

It should be noted that the technique used for corona loss detection is dependent on three important factors. First, the antenna current metering circuit must accurately indicate the current at the transmitter output. Second, there should be minimal losses between the transmitter output and the antenna input. Third, the antenna current panel meter must be read as accurately as possible. If these three conditions are met, then the recorded current will be the true antenna current, and any indication of non-linearity between field strength and antenna current will be indicative of corona losses.

3.0 FIELD STRENGTH MEASUREMENT SITES

A total of 20 sites were used for field strength measurements. As shown in Figure 1 these sites were divided for convenience into two groups; those on the west, southwest, and center portions of Oahu and those on the southeast, east, and northeast side of Oahu. The sites were chosen, in general, to obtain as many locations as possible around the Island away from highly industrialized or populated areas. Many of the sites were at beaches or parks located around the coast of Oahu. Because of the relatively small size of Oahu and the location of the NPM transmitting antenna system, some sites on the west coast were within the distance limits where the contributions of the induction field to the total measured electromagnetic field cannot be neglected. The necessary modifications to the measured field strengths at these locations were made in processing the data.

Each site was chosen so as to be well away from any obstacle that was believed to be a possible source of a local field anomaly. As mentioned previously the tests prior to 2 December 1971 were most helpful in attaining this goal because they enabled NRL representatives to investigate the measurement sites and to relocate those sites where anomalies in the field strength were discovered, before the special measurement work was begun. Consequently the field measurements were completed in an efficient manner when the special transmissions became available.

4.0 DATA PROCESSING

The field strength measurement data were tabulated in log books, and at the end of each series of measurements, the data were reviewed to determine the reliability of the individual data samples. This review was based on the depths of the loop antenna nulls, and the scatter of plotted data points on a field strength versus distance curve. After the data were reviewed and found acceptable, the corrected field strength, E, for each measurement was tabulated after applying appropriate meter correction factors.

The field strength meters, employing a shielded loop antenna, measured the total magnetic field which is the resultant of the induction and radiation fields. The effect of the induction field on the total magnetic field was calculated and the magnitude of this effect was eliminated from the field strength measurements after the meter correction factors had been applied. The induction field effects diminish rapidly as distance and frequency increase. For the dual antenna array at a distance of 9.5 kilometers (site C) and at a frequency of 14.7 kHz, 0.48 dB of the total magnetic field is the result of the effect of the induction field. At this same frequency, and at a distance of 21 kilometers (site K), the contribution of the induction field to the total field is reduced to 0.10 dB. At 28.5 kHz the induction field accounts for only 0.13 dB of the total magnetic field at the shortest distance used, 9.5 kilometers.

After applying the meter correction factors and taking into account the effects of the induction field, the field strengths were normalized to a constant antenna current for each transmission frequency. For most of the special transmissions for these measurements, the NPM antenna current, I_a, was adjusted to the same value at a particular frequency, and this was the antenna current used for normalization. The corrected field strengths normalized to a constant antenna current were then normalized to a distance, d, of 100 kilometers and identified as E_{Id}.

The number of field strength measurements made at each site and each frequency were essentially the same for all frequencies except for the dual antenna array and the east antenna array at 23.4 kHz. For these two antenna configurations at 23.4 kHz, some measurements were made during the CEMC tests. In order to avoid giving undue weight to any site, all measurements at a site for a particular frequency were averaged (arithmetic mean), and those individual site averages were then used in determining the overall average (arithmetic mean) field strength normalized to a constant antenna current and distance $\bar{E}_{Id}$. Since the

average field strength $\overline{E}_{Id}$ in millivolts per meter, was normalized to a distance of 100 kilometers, the expression for the radiated power, P_r, in kilowatts, reduces to

$$P_r = \overline{E}_{Id}^2/9 \qquad (4\text{-}1)$$

The radiation resistances, R_r, in ohms, were calculated using the equation

$$R_r = P_r/I_a^{\,2} \qquad (4\text{-}2)$$

where P_r is the radiated power in watts and I_a is the corresponding nominal value of antenna current in amperes.

The values for the antenna effective height, h_e, in meters, were calculated using eq. (2-3), which, since $\overline{E}_{Id}$ is normalized to a distance of 100 kilometers, reduces to

$$h_e = 7.96\text{x}10^4\ \overline{E}_{Id}/I_a f \qquad (4\text{-}3)$$

where I_a is the same as used in eq. (4-2) and f is the frequency in kilohertz.

5.0 RESULTS AND DISCUSSIONS

The VLF transmitting antenna system for NPM is normally operated in the dual array configuration (i.e. the east and west arrays are driven in parallel), however, the antenna system can also be operated with either of the single arrays employed. Although the field strength measurements for each antenna configuration utilized the same number of field sites (20), the number of measurements for the dual and east array at the 23.4 kHz test frequency exceeded those for the west array. For the dual array the number of measurements at 23.4 kHz totaled 64 rather than 20 by utilizing the CEMC tests on 23 and 24 November. The east array measurements at 23.4 kHz totaled 36 by utilizing the CEMC tests on 26 November. For the west array the 14.7 kHz test frequency was excluded, however, 20 measurements were made at each of the other test frequencies. The test to determine the possible onset of corona was performed on 7 December 1971 after all other required tests had been completed. The antenna was in the dual array configuration and operated at 14.7, 23.4, and 28.5 kHz test frequencies.

5.1 Dual Array Operation

The measured field strength values corrected for receiver factors and normalized to a constant antenna current, I_a, are presented in Figures 2 through 6 for the NPM antenna operating in the dual array configuration. The data exhibit very little scatter about the average inverse distance curve.

In spite of the small scattering of the field strength data, the data do show definite local terrain effects. A statistical analysis was performed to determine if any one site was being weighted too heavily. It turns out that such was the case and therefore some measurements were discarded in favor of a smaller standard deviation and an improvement in the average normalized field strength.

The radiation parameters for the NPM antenna system operating in the dual mode are given in Table 1 and Figure 7. The field strengths as measured by NRL were further analyzed when the calculated radiation parameters were plotted because the least square polynomial curve fit was not as expected. Although every conceivable technique was used to analyze the data, a satisfactory curve to fit the plotted data was not forthcoming. As a result of this more thorough analysis, as mentioned previously, some measurements were discarded because of inconsistencies and the values of the calculated radiation parameters did change. Since the field strength measurements did not seem to be responsible for the unusual shaped curves, other reasons must be found. One very likely source of error is in the antenna current readings, and as can be seen in equations (4-2) and (4-3) an error in antenna current, I_a, will change the values for radiation resistance, R_r, and effective height, h_e. As mentioned previously the meter used to read antenna current was a regular console panel meter movement with a temporary face plate marked off in evenly spaced graduations of 0 to 100. Depending on the frequency, the tick marks for the smaller currents (e.g. 400 ampere range) which were in the lower portion of the scale could be 20 to 30 amperes per division. Thus an error in reading of $\pm$ 5 amperes or more could occur with little difficulty and in turn the effective height could be changed by one to two meters. If, for example, the effective height at 16.6 kHz (see Figure 7) were increased by 2 meters from 191.9 to 193.9 meters the overall curve fit for the dual array would improve. Another possible source of error is the method used for detecting the antenna current. The accuracy of detection technique is at best 5 percent, and if more than minimal losses occur between the transmitter output and the antenna input, the error is even larger.

5.2 East Array Operation

The NPM transmitting system can be operated with one of the arrays either east or west disabled. For east array operation, the west array feedline is disconnected and the antenna grounded, thus enabling the driven east array parameters to be measured. The radiation parameters for the east array were measured in the same manner and at the same test frequencies as for the dual array configuration. The field strengths for the east array operation are given in Figures 8 through 12 and exhibit the same general distribution as for the dual array operation. The same statistical analysis that was performed on the dual array was used to determine if any one site for the east array measurements was being weighted too heavily. The result was a smaller standard deviation and an improvement in the average normalized field strength.

The radiation parameters for the NPM antenna system operating with only the east array are given in Table 1 and Figure 7. The apparent inconsistency at the lower frequencies as shown in Figure 7 could be due, as was mentioned for the dual array, to the errors in panel meter readings and/or antenna current detection techniques.

5.3 West Array Operation

During the period of the measurement program the field strength of the NPM transmitting system with the west antenna array only being driven was measured. The radiation parameters for the west array were measured in the same manner as for the dual and east array but at only four test frequencies. The field strengths for the west array operation are given in Figures 13 through 16 and show the same tendencies as for the dual and east array operation. The west array standard deviation and normalized field strength shown in Table 1 are a result of the same statistical analysis used for the dual and east array configurations.

The radiation parameters for the NPM antenna system operating with only the west array driven are given in Table 1 and Figure 7. Notice should be taken of the values of radiation resistance and effective height at the four test frequencies because these values are less than the dual array and greater than the east array configuration. The plots of effective height and radiation resistance for the west array appear to result in a smooth curve, but without any field strength measurements below 16.6 kHz the curve cannot be extended to the 14.7 kHz test frequency nor can the curve fit be considered absolutely correct through the measured points.

5.4 Corona Tests

The test to determine the possible onset of excessive corona losses was performed employing only the dual array antenna configuration. The antenna current was varied in given steps over the 14.7 kHz, 23.4 kHz, and 28.5 kHz test frequencies and the resultant field strengths measured at two fixed sites. As can be seen in Figures 17 through 19 the plots of radiated power versus antenna current exhibit a slight S shape and at the 14.7 kHz test frequency a flattening off is apparent near the high end of the radiated power. A check of possible corona onset at the 16.6 kHz and 19.8 kHz test frequencies in addition to those measured may have been helpful, but at the time these tests were conducted, the NPM transmitter was experiencing some difficulties. Numerous kickdowns of the transmitter power had occurred during the entire series of tests by CEMC and during the field strength tests by NRL. Consequently, when the corona tests were conducted on the NPM transmitting system, the possibility of transmitter breakdown was considered and therefore only the lowest test frequency 14.7 kHz, the operating frequency 23.4 kHz, and the highest test frequency 28.5 kHz were selected. Even though only three test frequencies were used, the test still required an excessive amount of time (8 hours) to accomplish because of numerous transmitter power shutdowns.

As was pointed out earlier in the report, the technique used to detect the possibility of corona loss depends on three important factors. The antenna current metering circuit must accurately indicate the true current at the transmitter output, there should be minimal losses between the transmitter output and antenna input, and the antenna current must be read as accurately as possible. For example, an inspection of Figures 17a and b will reveal an irregularity at an antenna current of 905 amperes for the 14.7 kHz test frequency at two measurement sites. Two different field strengths were measured at the same antenna current (905 amps), but at separate times during the tests. The higher field strength was measured at the initial tune up of the transmitter and the lower field strength was measured when the antenna current was stepped through a range of currents for the corona test. It is difficult to point out the exact cause of this irregularity because it could be one thing or a combination of problems. Either the antenna current detection techniques are at fault, the antenna current was read incorrectly, the system is going into corona, or a combination of these difficulties is responsible. More tests are required before any definite conclusions can be made, but an irregularity does exist in the corona test results and it was witnessed at two different measurement sites.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

1. Garner, W. E. and Raudenbush, J. E., "Program for the Determination of the Effective Height and Radiation Resistance of the VLF Transmitting System at NAVCOMSTA, North West Cape, Australia", NRL Memorandum Report 1606, April 23, 1965.

TABLE 1

Measured Antenna Radiation Parameters at Lualualei

Antenna	Freq. (kHz)	No. of sites	Number of Measure.	Antenna Current (Amperes)	Radiated Power kW	Radiated Power dB>1kW	Radiation Resistance (Ohms)	Effective Height (Meters)
Dual	14.7	20	20	947	113.7	20.56	0.127	182.6
"	16.6	20	20	1055	198.8	22.98	0.179	191.9
"	19.8	20	20	1227	444.0	26.47	0.295	206.7
"	23.4	20	64	1220	607.6	27.84	0.408	205.8
"	28.5	20	20	1032	652.1	28.14	0.612	207.0
East	14.7	20	19	593	33.6	15.26	0.096	158.5
"	16.6	20	20	664	62.0	17.92	0.141	170.3
"	19.8	20	19	800	127.6	21.06	0.199	170.0
"	23.4	20	36	911	248.2	23.95	0.299	176.2
"	28.5	20	20	1040	505.7	27.04	0.468	180.9
West	16.6	20	20	572	50.2	17.01	0.154	177.9
"	19.8	20	20	690	118.8	20.75	0.249	190.1
"	23.4	20	19	810	232.5	23.66	0.354	191.8
"	28.5	20	20	975	505.6	27.04	0.532	192.9

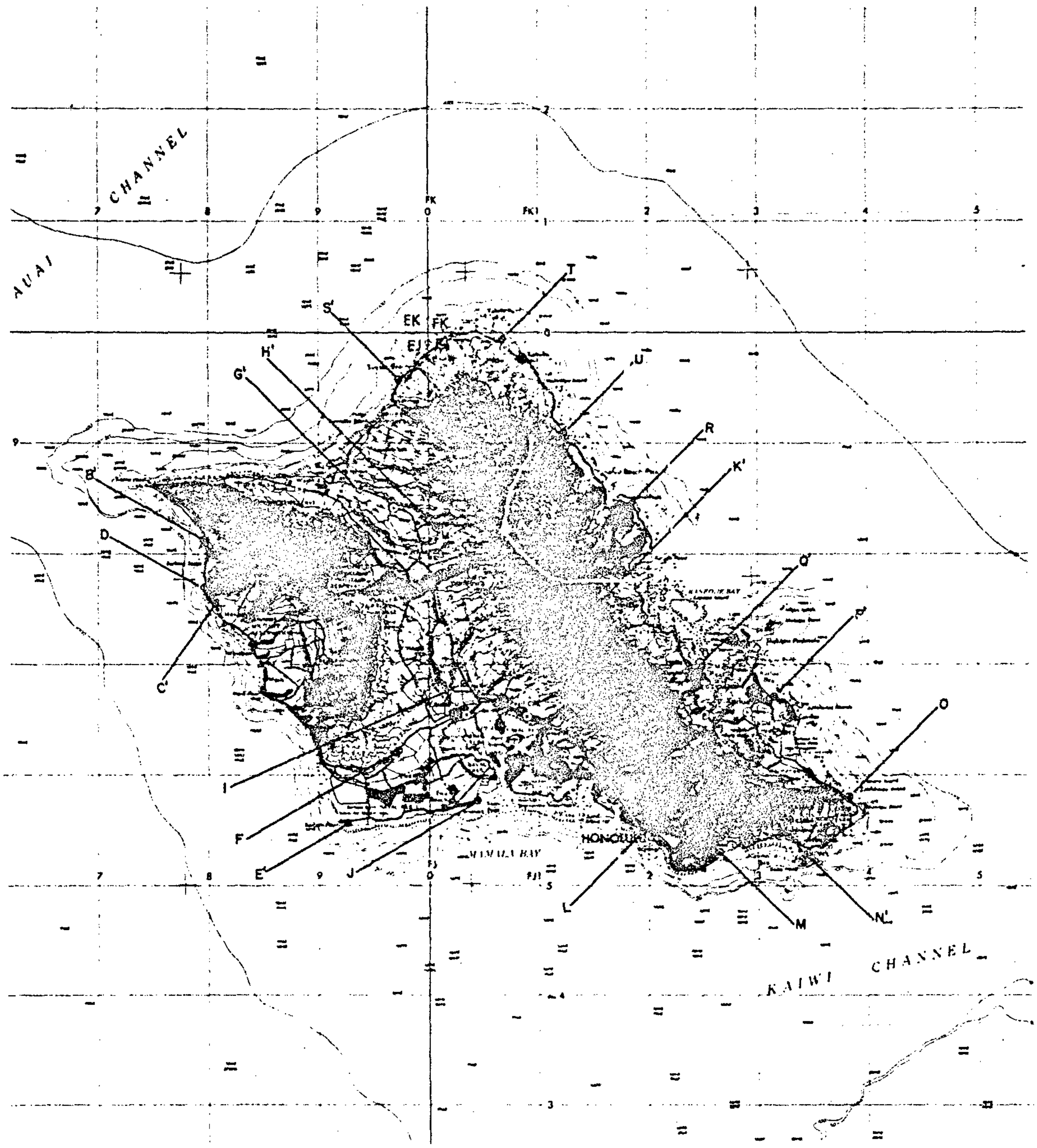


Fig. 1 - Oahu, Hawaii, sites used for field strength measurements.

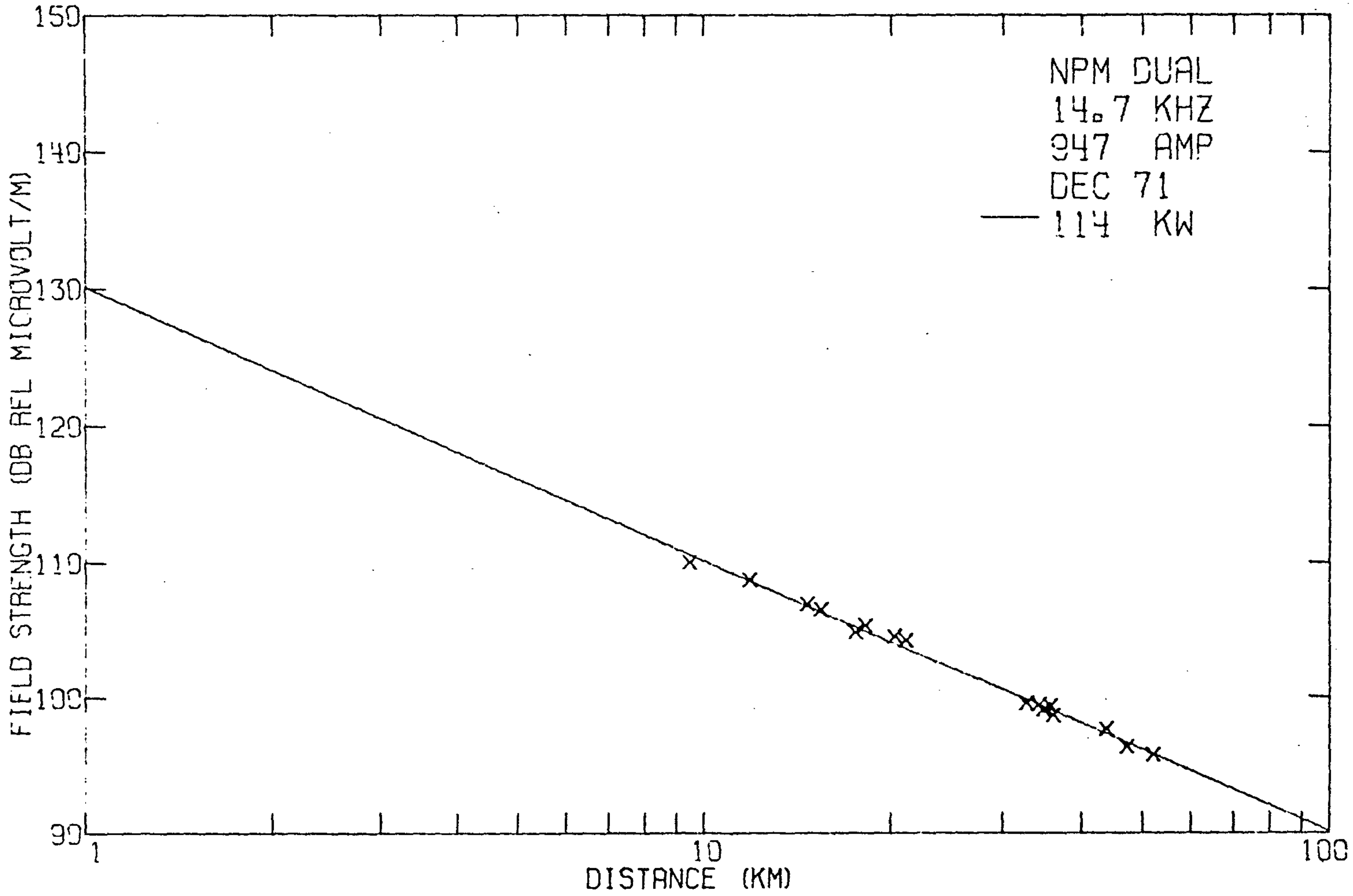


Fig. 2 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with dual array at 14.7 kHz.

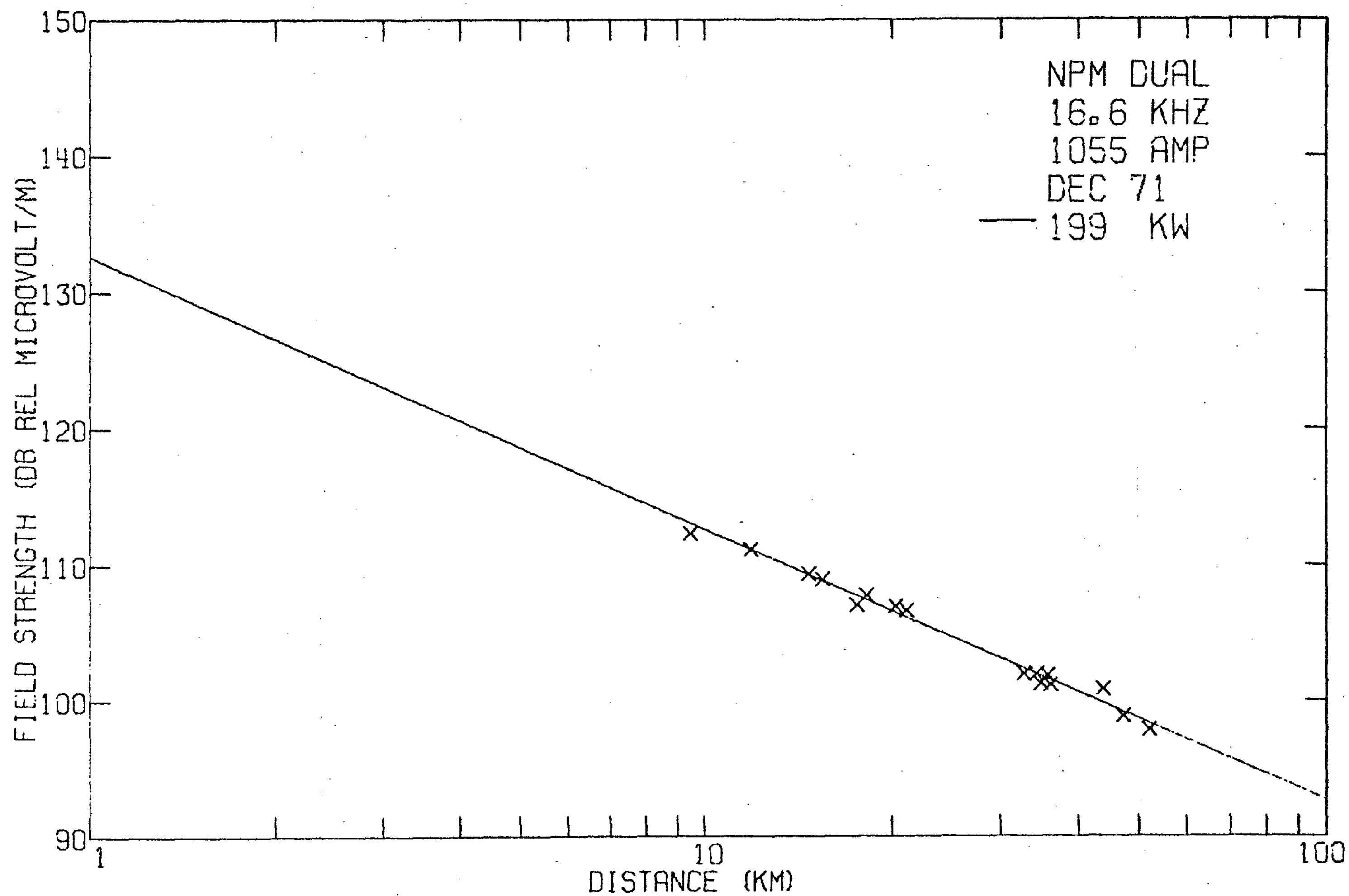


Fig. 3 – Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with dual array at 16.6 kHz.

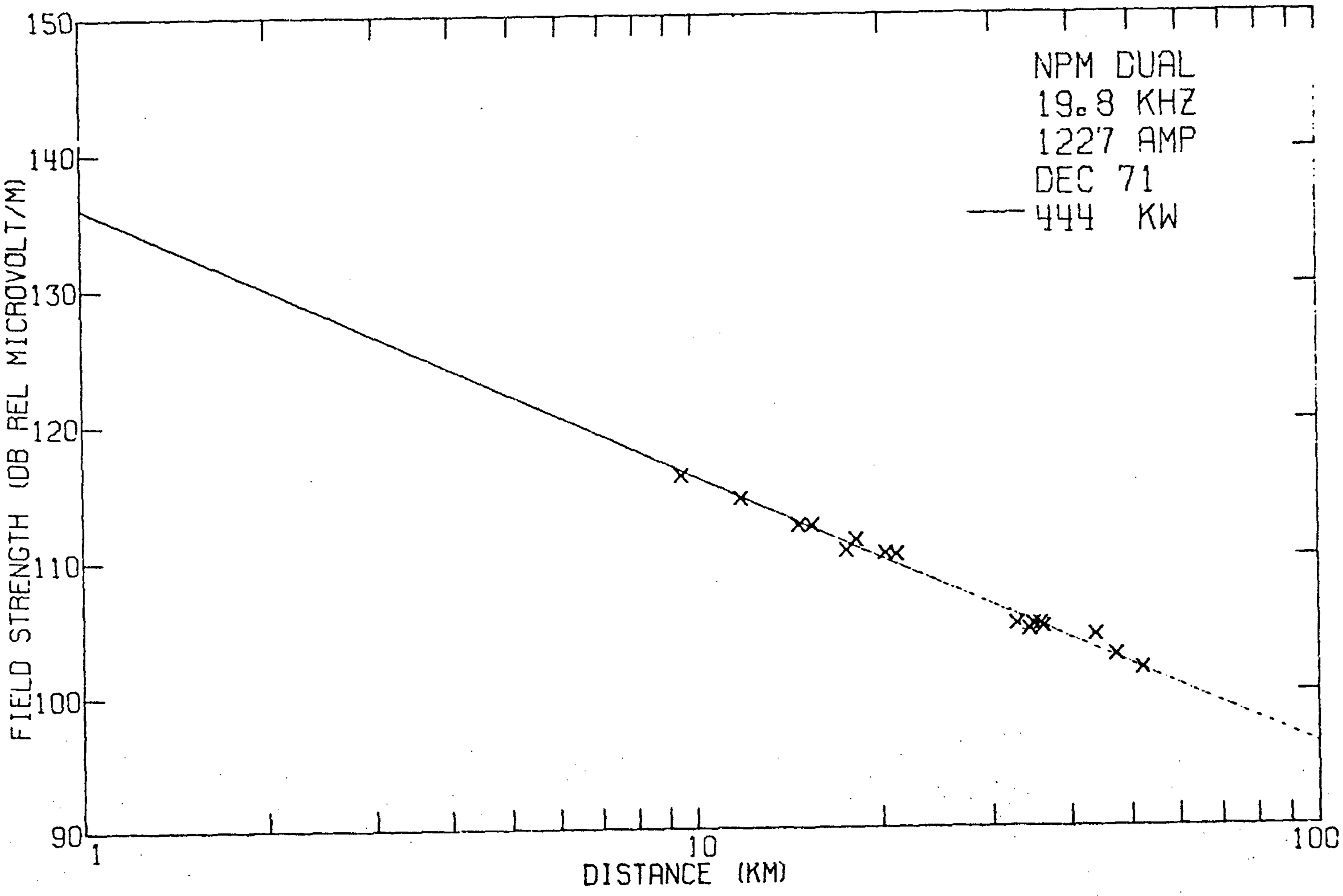


Fig. 4 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with dual array at 19.8 kHz.

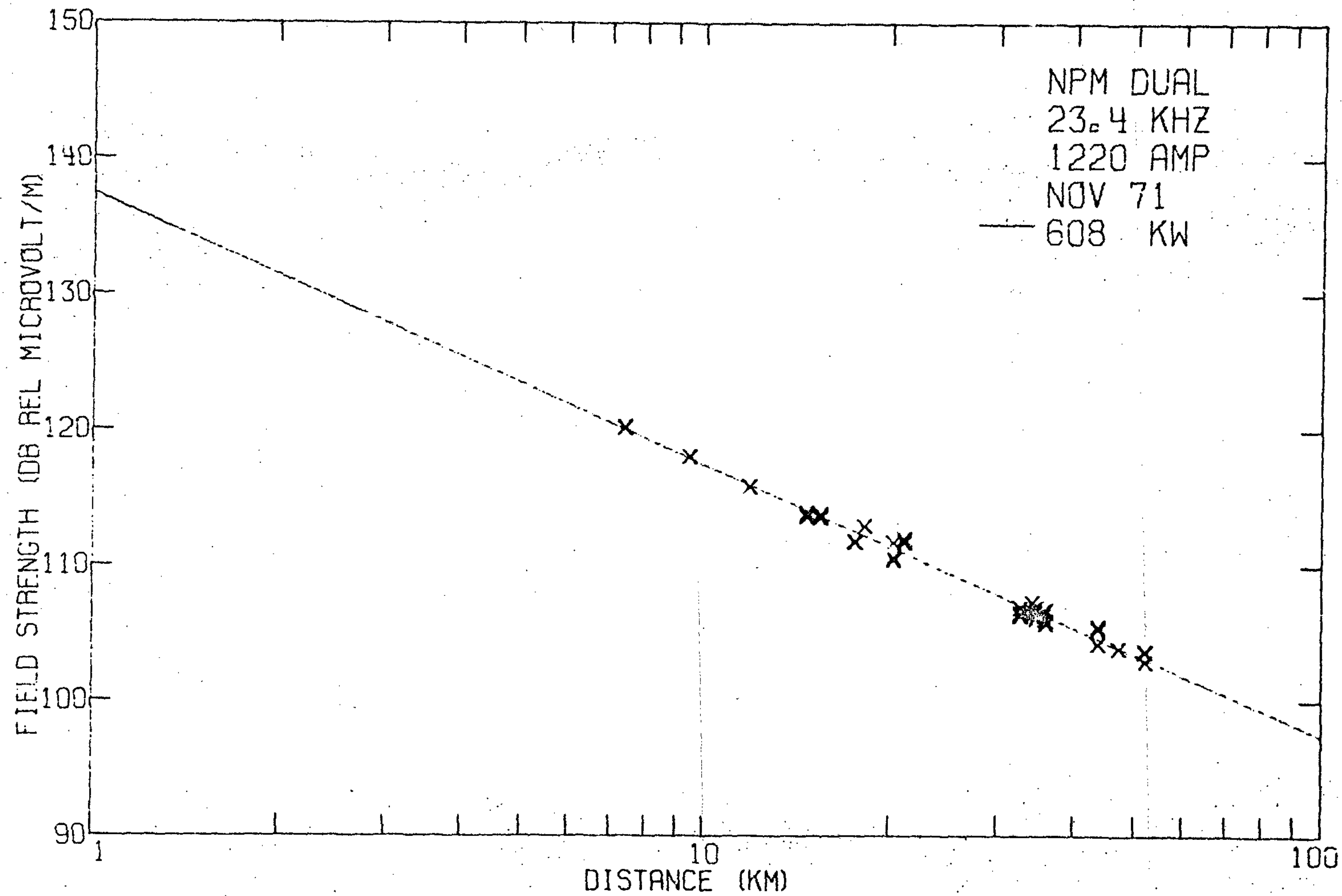


Fig. 5 – Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with dual array at 23.4 kHz.

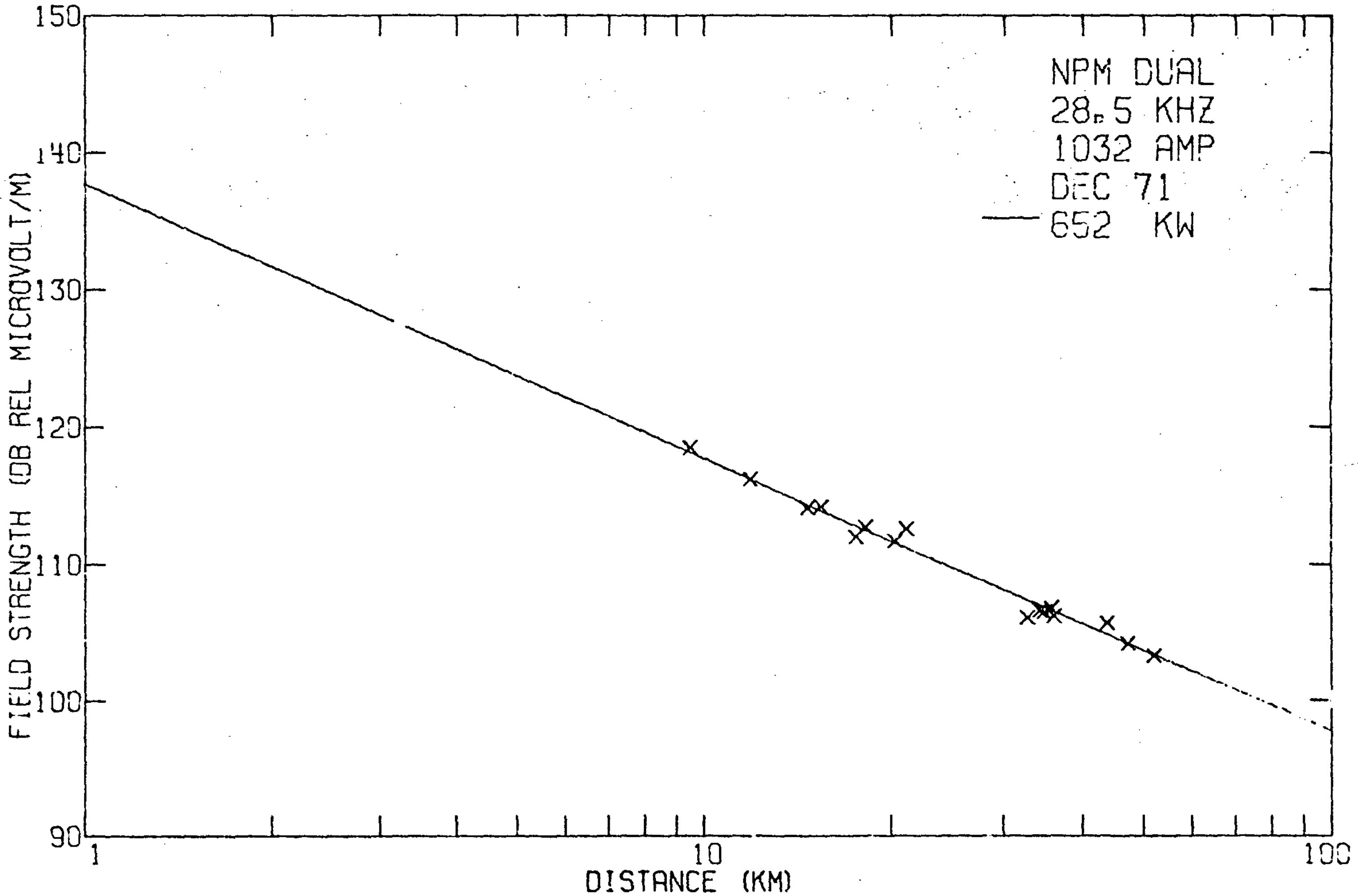


Fig. 6 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with dual array at 28.5 kHz.

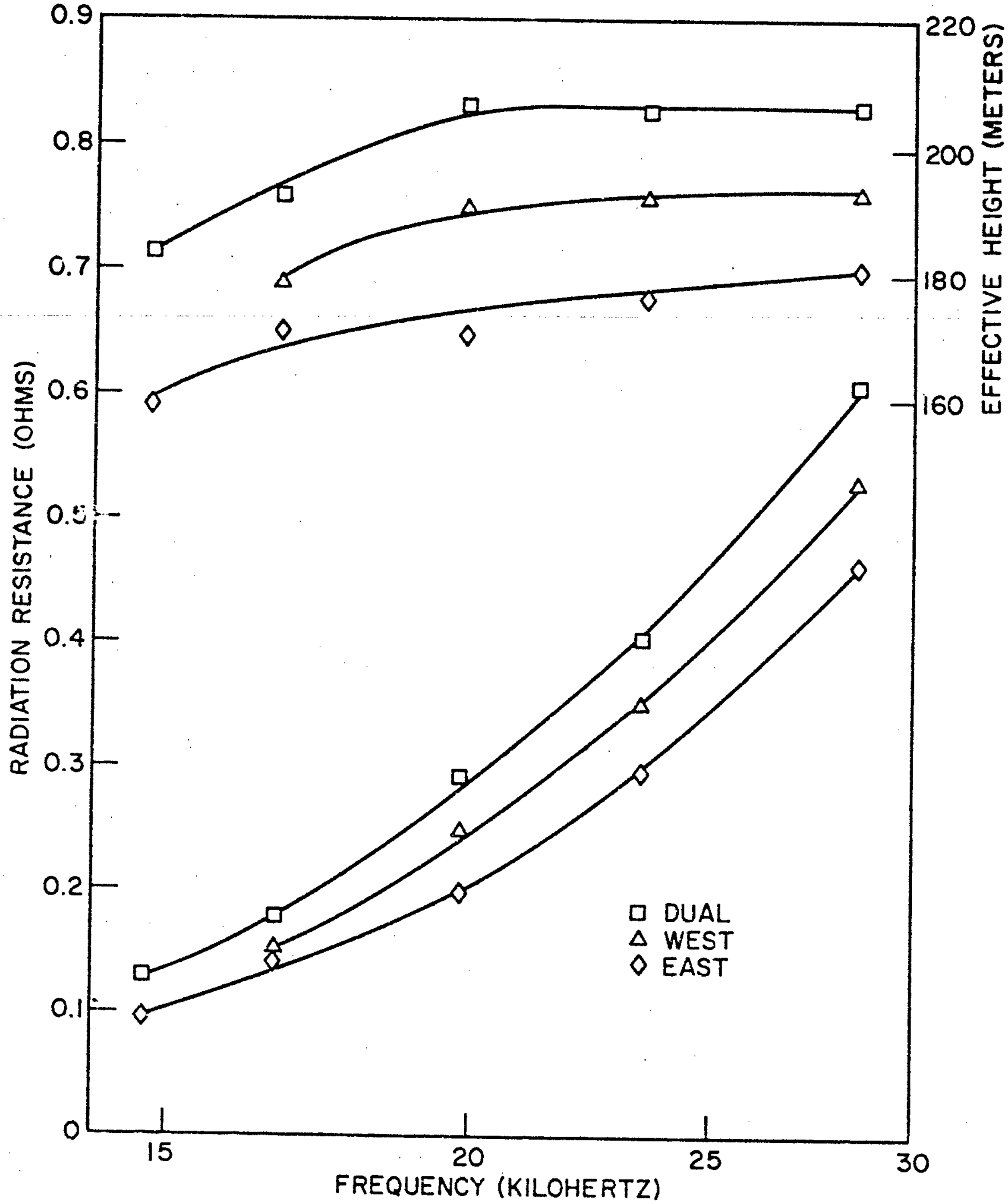


Fig. 7 - Radiation resistance and effective height of the NPM antenna system operating in the dual mode, single east mode and single west mode as a function of frequency.

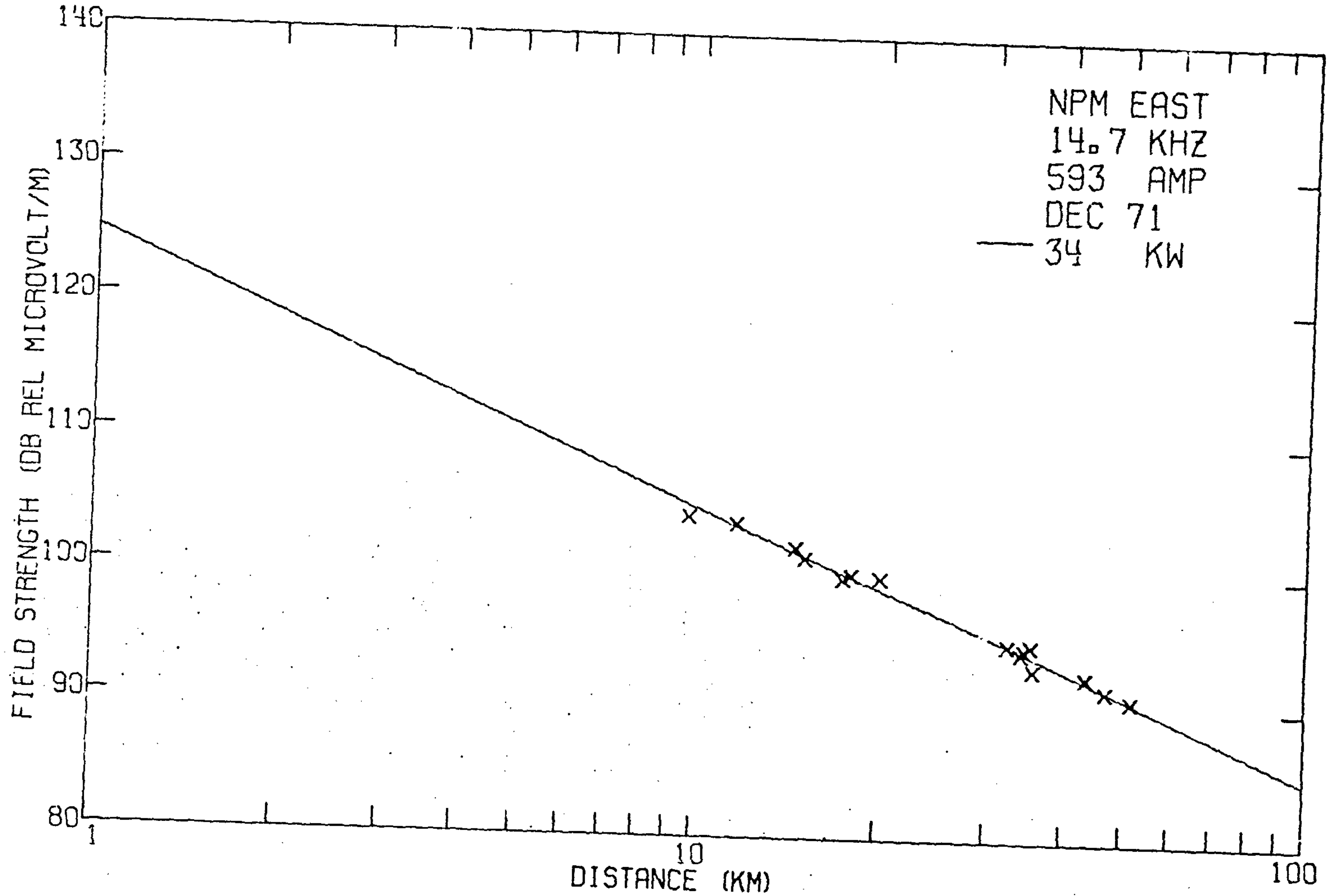


Fig. 8 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with the single east array at 14.7 kHz.

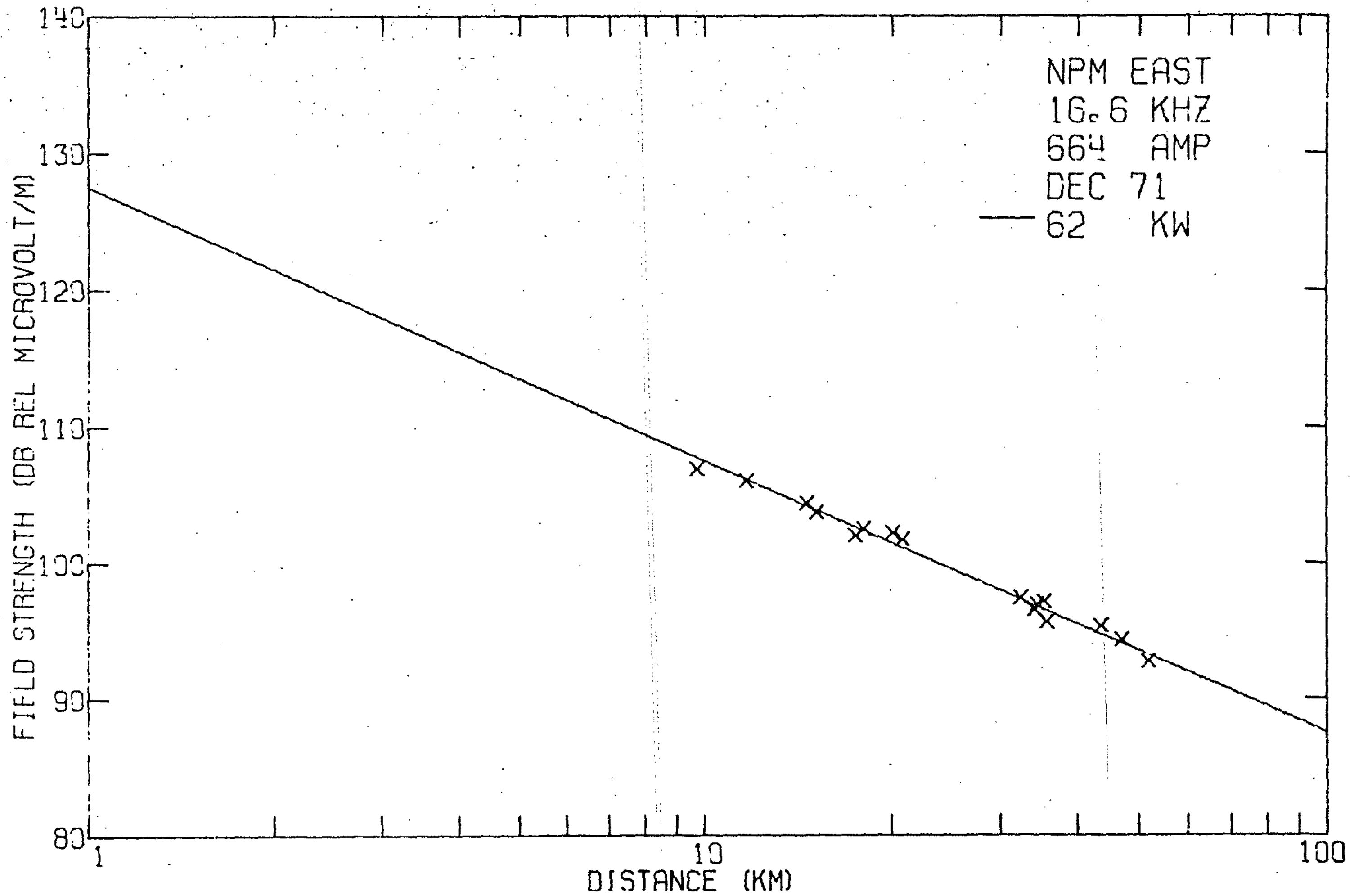


Fig. 9 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with the single east array at 16.6 kHz.

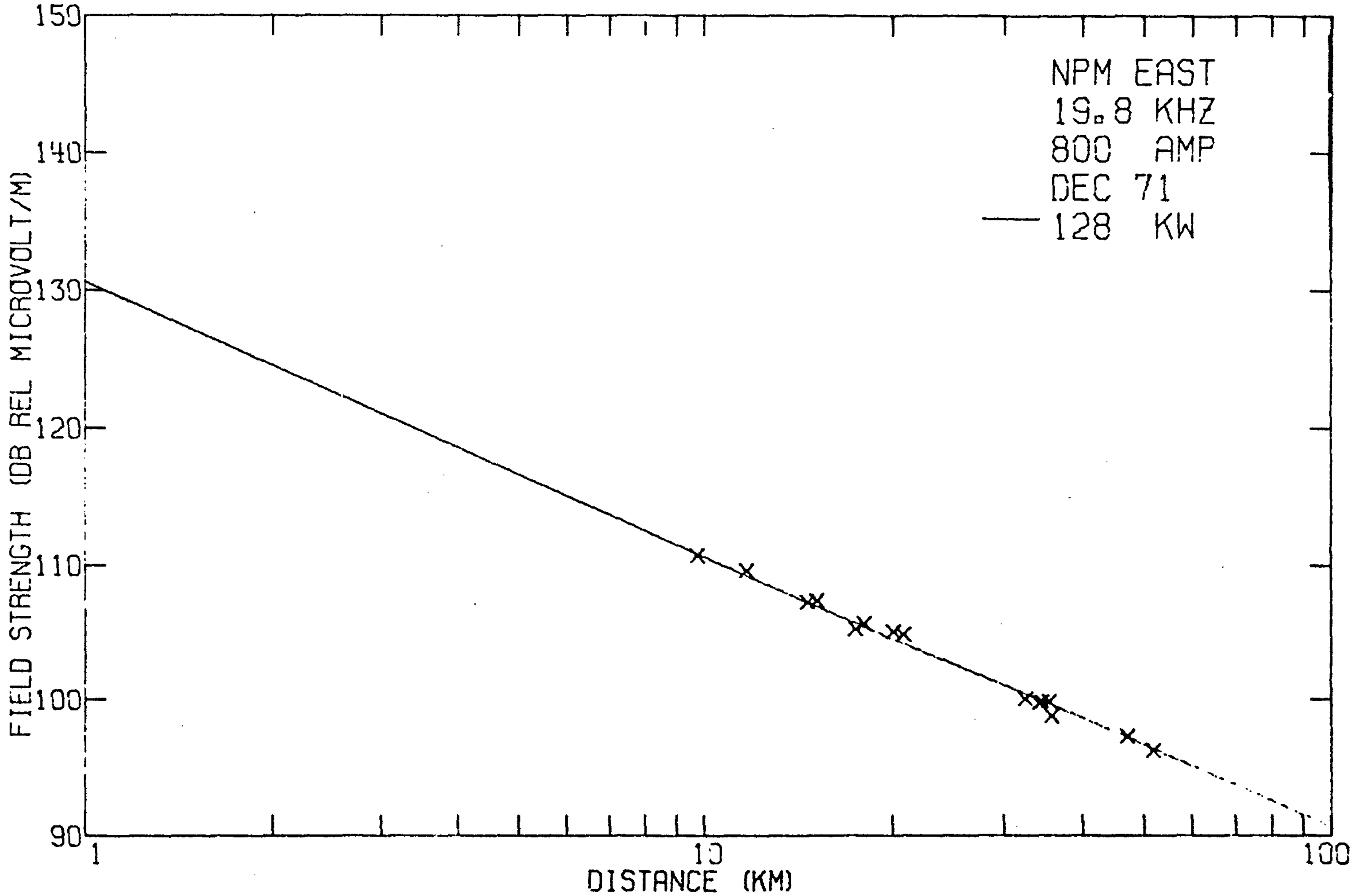


Fig. 10 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with the single east array at 19.8 kHz.

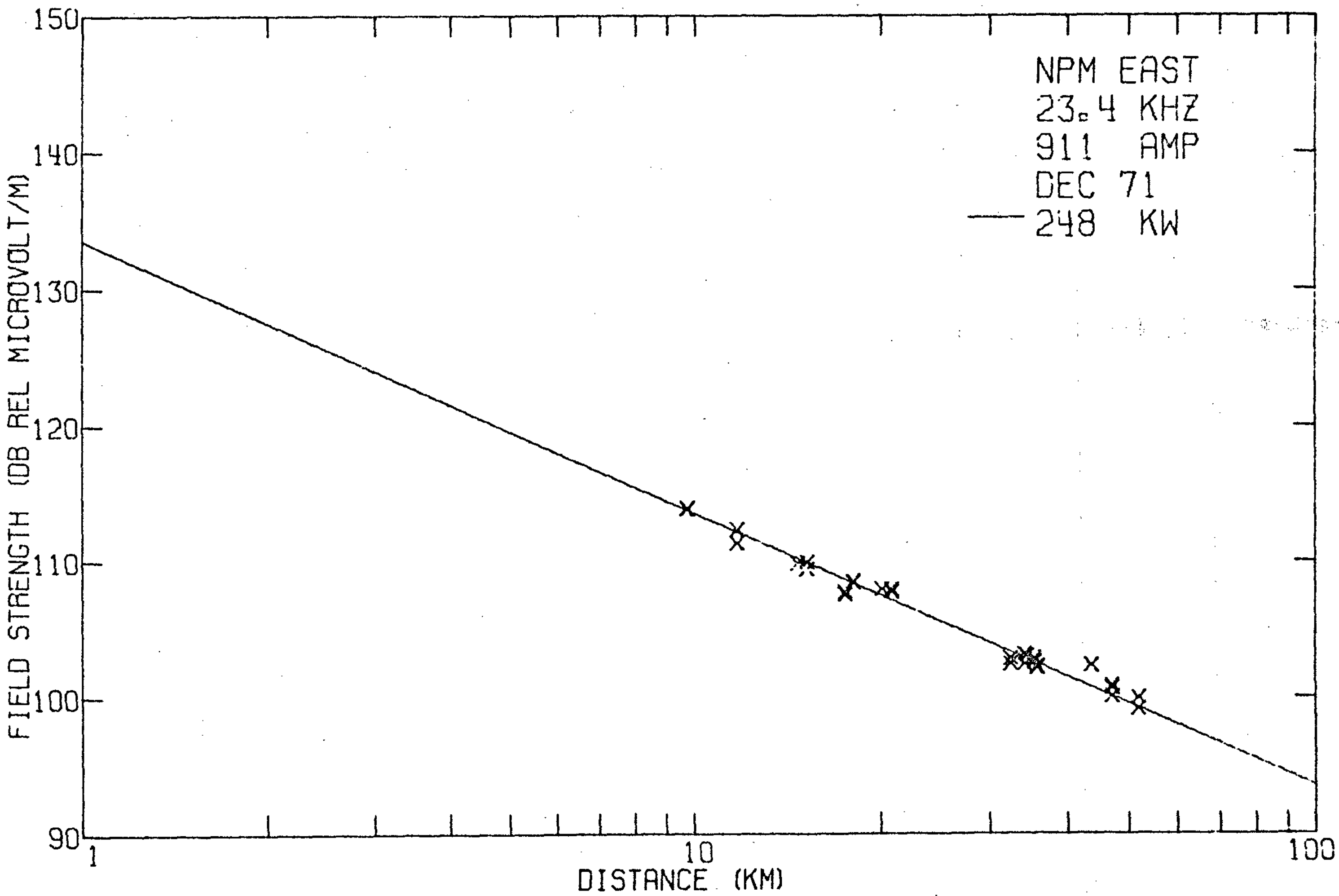


Fig. 11 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with the single east array at 23.4 kHz.

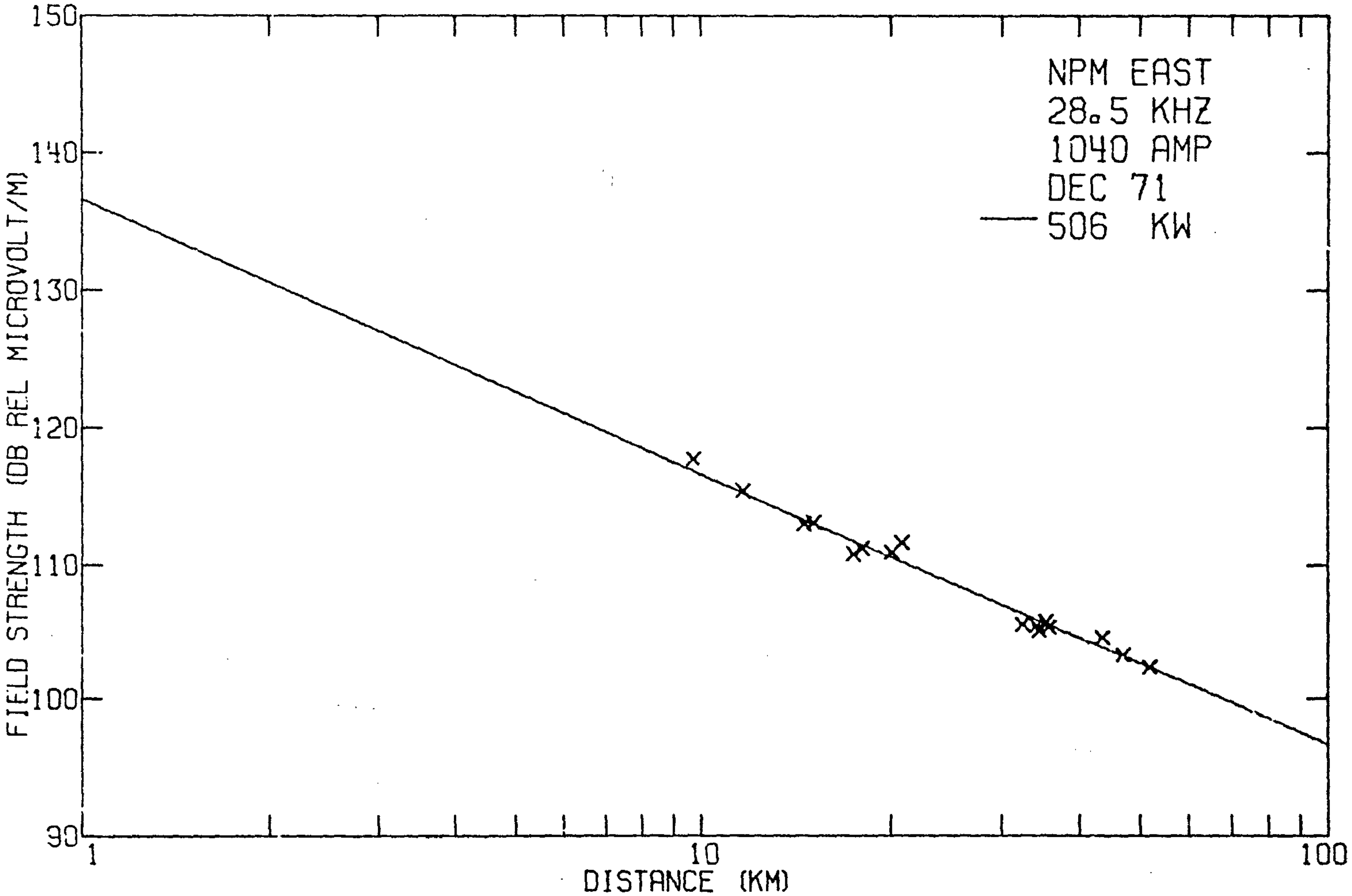


Fig. 12 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with the single east array at 28.5 kHz.

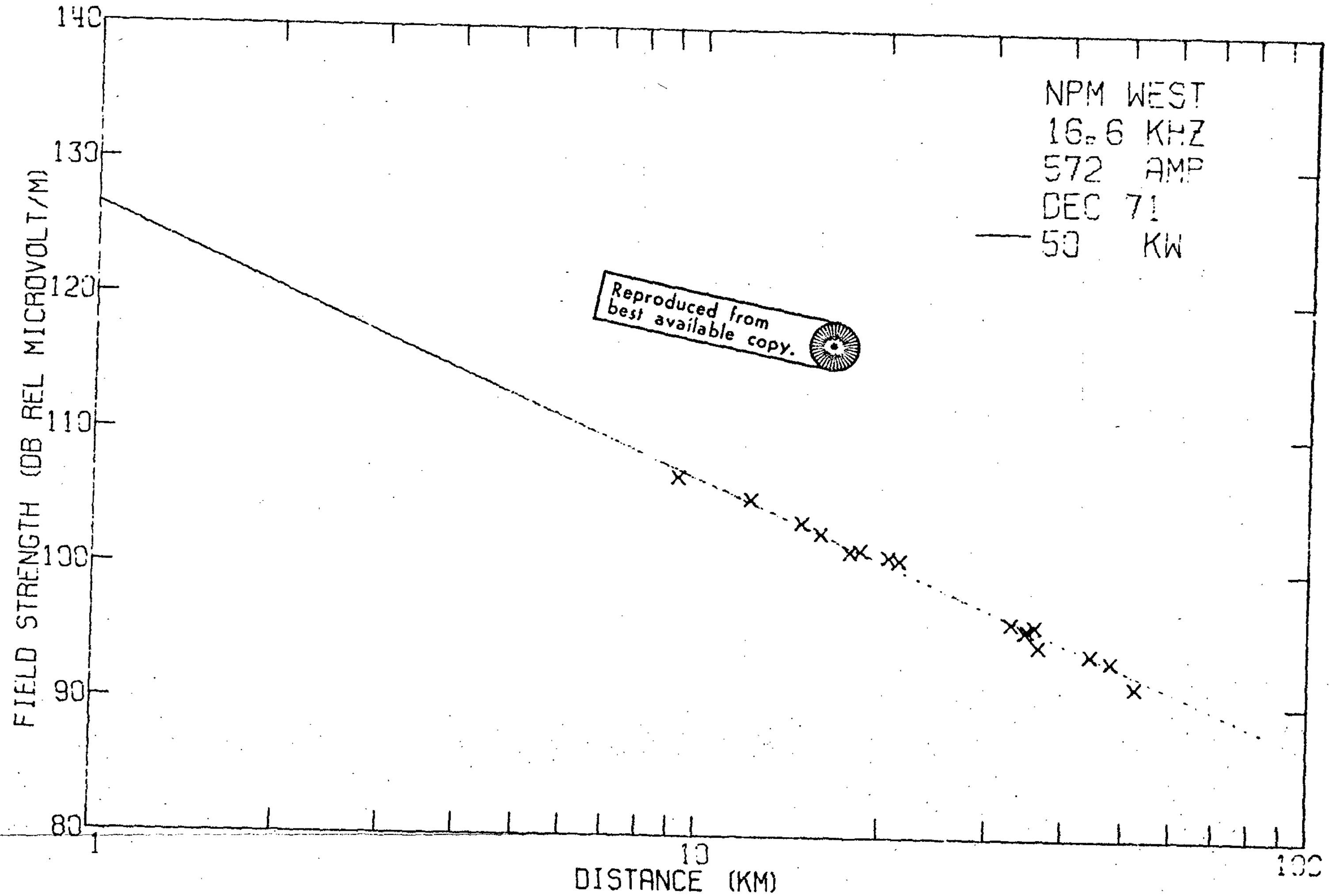


Fig. 13 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with single west array at 16.6 kHz.

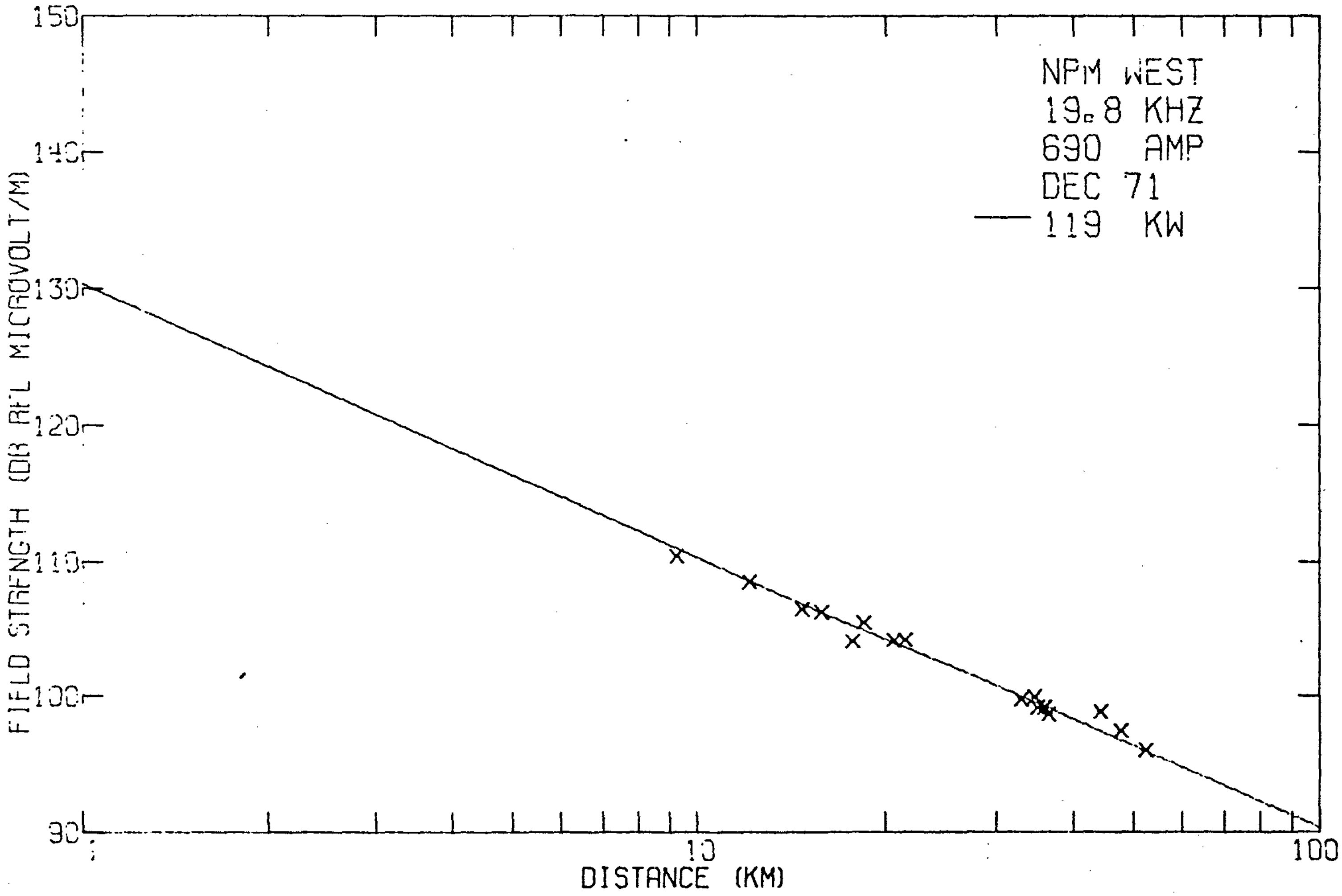


Fig. 14 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with single west array at 19.8 kHz.

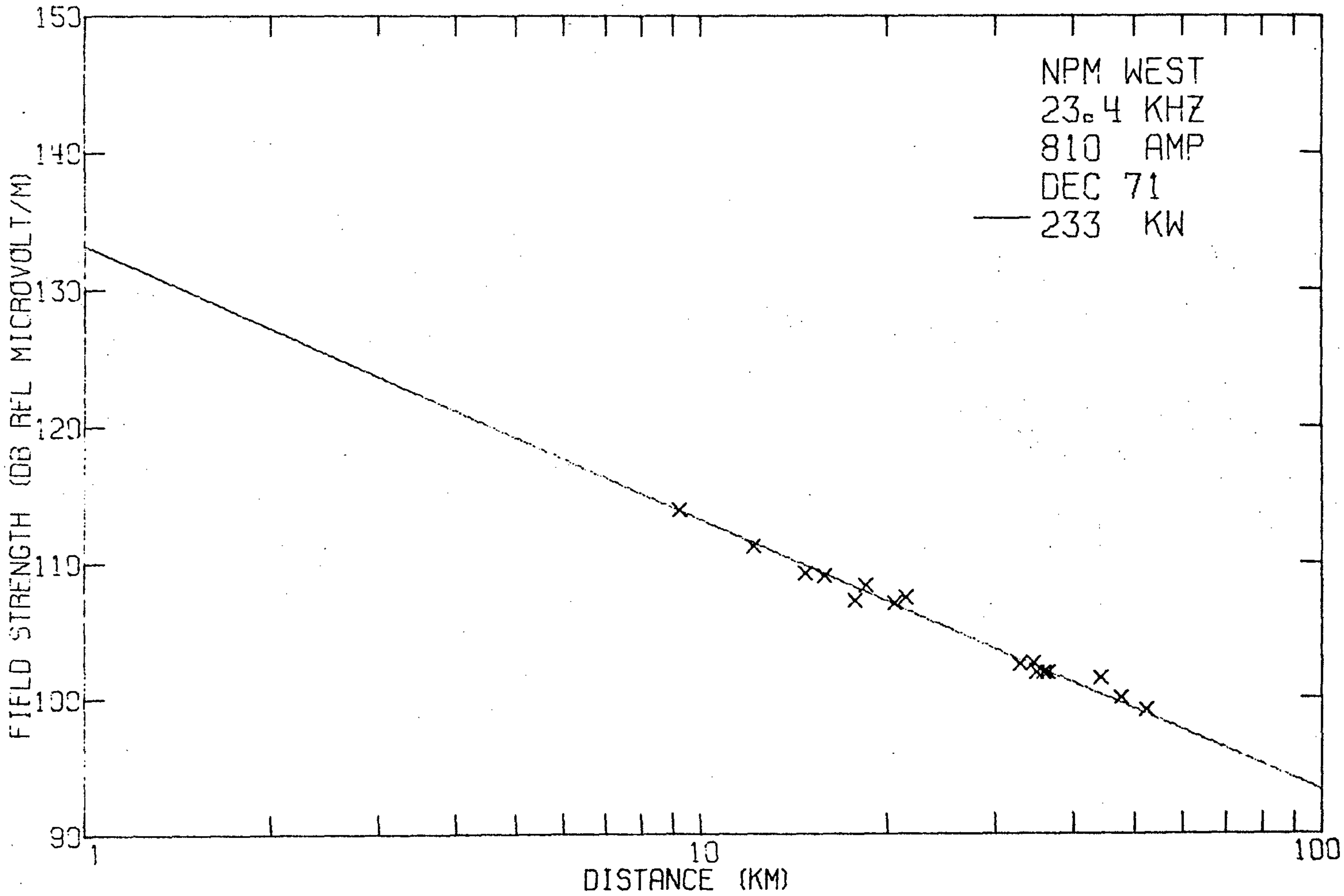


Fig. 15 – Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with single west array at 23.4 kHz.

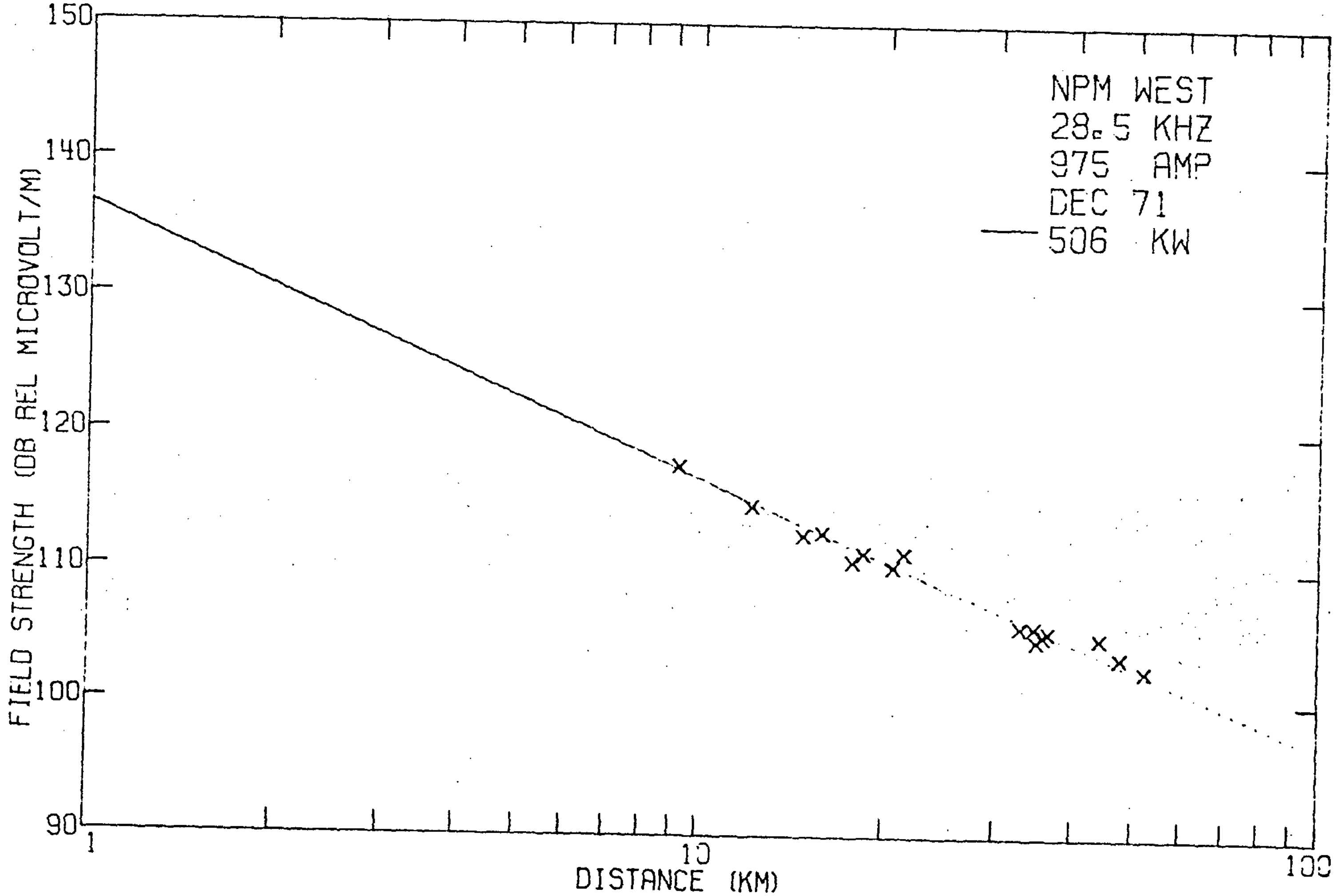
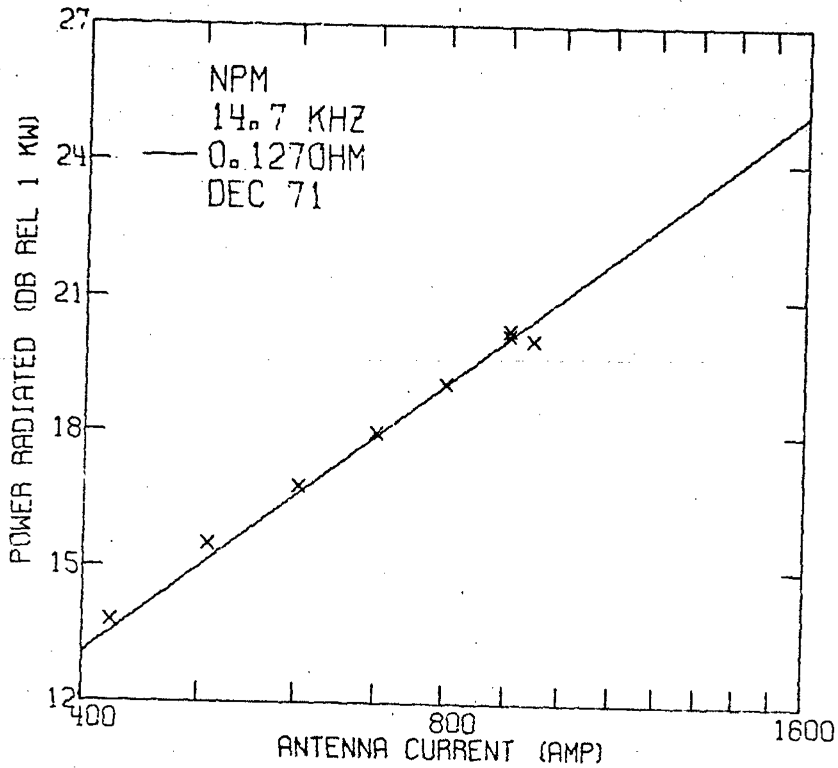
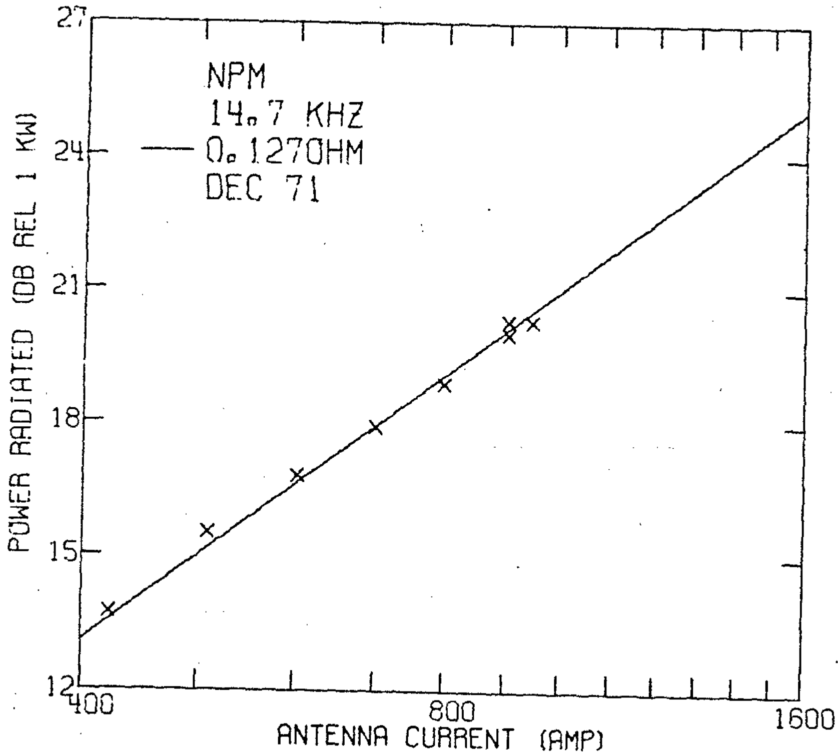


Fig. 16 - Field strength normalized to a constant antenna current as a function of distance from the NPM antenna operating with single west array at 28.5 kHz.

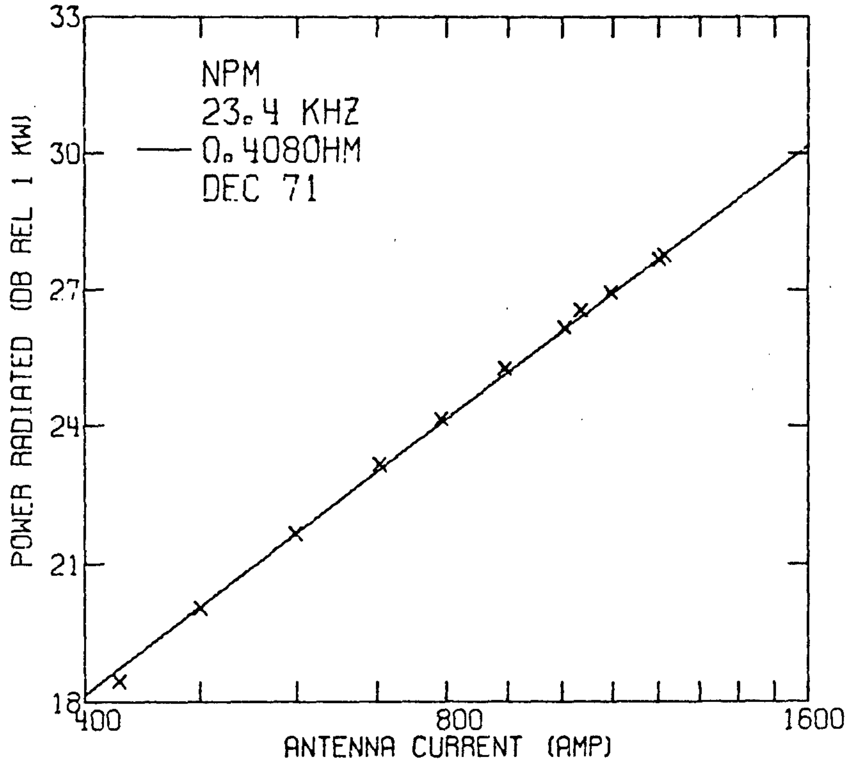


(a)

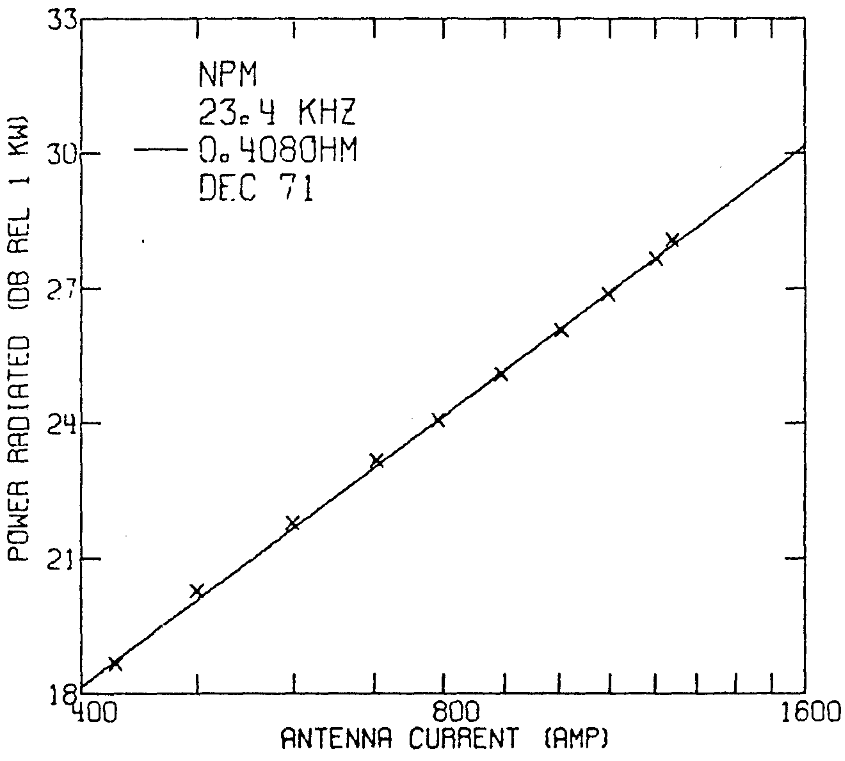


(b)

Fig. 17 - Radiated power as a function of antenna current for the NPM antenna system operating with dual array at 14.7 kHz. (a) site C, (b) site M.



(a)



(b)

Fig. 18 - Radiated power as a function of antenna current for the NPM antenna system operating with dual array at 23.4 kHz. (a) site C, (b) site M.

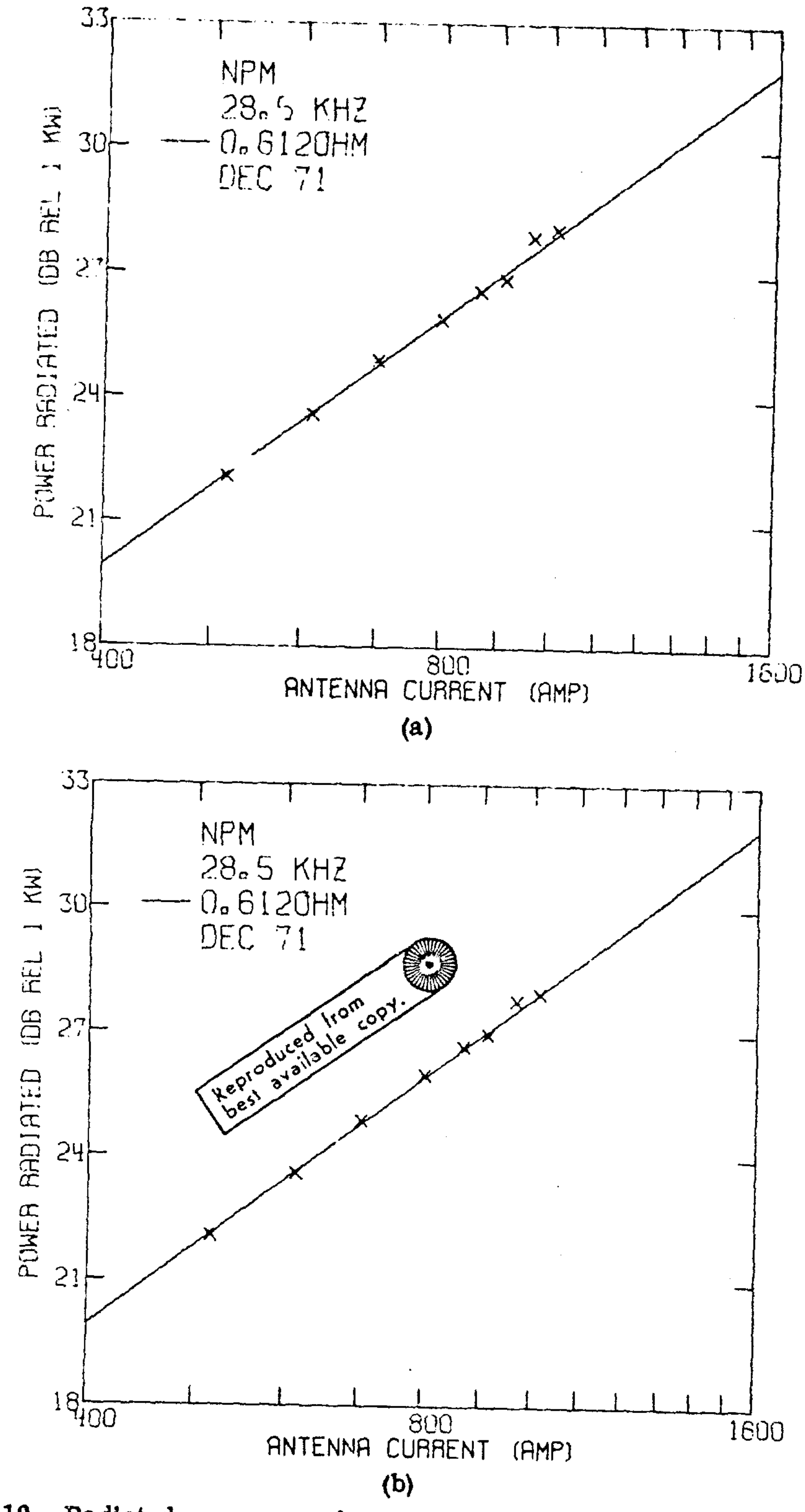


Fig. 19 - Radiated power as a function of antenna current for the NPM antenna system operating with dual array at 28.5 kHz. (a) site C, (b) site M.